

VHE Astronomy before the New Millennium

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I INTRODUCTION

In planning this workshop the organizers suggested that a review of new TeV γ -ray observations at the beginning might obviate a need for separate submissions from individual groups (which would be presented anyway at the ICRC) and thus permit the program to be devoted to technical developments, interpretations and new programs. In practice, this did not work too well since many groups wished to personally present their own results at the workshop also. Therefore I tried to present some synthesis of the results as seen in August, 1999. In principle, these are pre-workshop but in practice since many of the ICRC papers were available (courtesy of astro-ph) and others were sent directly to me, I have been able to include many of the most recent results. As usual, the printed ICRC papers do not contain the whole story since many authors still regard the pre-conference papers as place holders with the real results to be presented orally at the conference. Hence the proceedings are archaic as soon as they are printed (or recorded on CD)!

I will concentrate on the TeV observations reported since the last workshop (Kruger Park, August, 1997). I will not discuss the impressive technical improvements reported from many Very High Energy (VHE) observatories, nor describe the new VHE observatories that have come on-line (or are due shortly to come on-line) nor the many interpretations now reported for the VHE observations. Suffice to say that VHE astronomy is still observation-driven and that theoretical VHE astrophysics still lags as a predictive discipline.

More general reviews of VHE γ -ray astronomy can be found elsewhere [1,2].

II STANDARDS OF CREDIBILITY

It is well known that VHE γ -ray astronomy has had a rather murky past in that many sources were claimed in the eighties which were never verified. In fairness it should be noted that in the balloon era of 100 MeV γ -ray astronomy (in the sixties) there were also many unverified claims which were only resolved with the advent

of satellite astronomy and the use of reliable statistical methods. Nevertheless VHE γ -ray astronomy suffers from the problems that the detector medium is the atmosphere over which the experimenter has no control and that non-statistical effects due to atmospheric/detector conditions are a perpetual problem. This is primarily so for optical techniques but it has yet to be demonstrated that air shower arrays are free of such effects. In such circumstances, some subjective bias in the data analysis, i.e., in data selection, is almost inevitable. It should also be remembered that this is a relatively new discipline (it is only ten years since the publication of the first verifiable observation) and hence its exponents are still feeling their way. In these circumstances it behooves all involved to adopt a conservative attitude to claims for the detection of new sources.

It was at the ICRC in Hobart, Australia in 1971 that Prof. A.E. Chudakov suggested that the acceptable standard of credibility for a new VHE γ -ray source should be 5σ . I have not been able to find a reference for this statement and I was not at the conference but I remember well the dismay with which we greeted this news on the return of our senior colleagues who attended. At that stage we had managed to accumulate a 3σ result on the Crab Nebula [3] which we thought bordered on the edge of credibility. A 5σ result seemed an impossible standard.

Years later I met Prof. Chudakov at the 14th Texas Conference on Relativistic Astrophysics; I reminded him of his 5σ credibility criterion (which had not been met on another source in the interval) and proudly announced that with the atmospheric Cherenkov imaging technique we now had a 9σ signal from the Crab. He paused for a moment and then said drolly: "I think I should have said 10σ ". He was right of course; a 5σ detection is not always entirely credible. But he was wrong also, for a 10σ detection by a single experiment using a new technique is almost as liable to be a systematic effect as a 5σ detection.

To be convincing, I suggest that we adopt a standard where a *really* credible source requires a 5σ detection coupled with an equally significant verification by another experiment. Ideally the " σ " should include the best estimate of potential systematic effects. This would qualify as a Grade A detection. A Grade B detection would then be the same but without the independent verification. Grade C would be a strong detection but with some qualifications: time variability or some other factors which introduce extra degrees of freedom.

III THE 1997 TEV SOURCE CATALOG

In his comprehensive rapporteur talk at the 25th ICRC, Chaman Bhat listed eleven sources of TeV gamma-rays based on observations reported at that meeting [4]. These were the SNR remnants, the Crab Nebula, PRS 1706-44, Vela, and SN1006; the AGNs, Markarian 421, Markarian 501 and 1ES2344+514; the binary, Centaurus X-3; and the pulsars, PSR B 1259-63, PSR B 1509-58, and PSR 1105-61. As we shall see below, all except the three pulsars (about which there have been no further reports of confirmed detections) appear in the 1999 catalog.

TABLE 1. Flux from the Crab Nebula

Group	VHE Spectrum (10^{-11} photons cm^{-2} s^{-1} TeV^{-1})	E_{th} (TeV)
Whipple (1991) [5]	$(25(E/0.4\text{TeV}))^{-2.4\pm0.3}$	0.4
Whipple (1998) [7]	$(3.2 \pm 0.7)(E/\text{TeV})^{-2.49\pm0.06_{\text{stat}}\pm0.04_{\text{syst}}}$	0.3
HEGRA (1999) [8]	$(2.7 \pm 0.2 \pm 0.8)(E/\text{TeV})^{-2.60\pm0.05_{\text{stat}}\pm0.05_{\text{syst}}}$	0.5
CAT (1999) [9]	$(2.7 \pm 0.17 \pm 0.40)(E/\text{TeV})^{-2.57\pm0.14_{\text{stat}}\pm0.08_{\text{syst}}}$	0.25
CANGAROO (1998) [10]	$(2.01 \pm 0.36)\times 10^{-2}(E/7\text{TeV})^{-2.53\pm0.18}$	7
Tibet HD (1999) [11]	$(4.61 \pm 0.90)\times 10^{-1}(E/3\text{TeV})^{-2.62\pm0.17}$	3

IV SOURCE SUMMARY

A Galactic Sources

The Crab Nebula

There is remarkable agreement now between the absolute fluxes and spectral shapes reported from observations of the Crab Nebula by imaging ACTs; the results from the Whipple, HEGRA, CAT and CANGAROO experiments are shown in Table 1. These are also in agreement with the flux reported in the first detections of the Crab [6,5] but this must be considered fortuitous in view of the large error bars in these early measurements. At least in the 300 GeV to 3 TeV range it is clear that the Crab can now be considered a standard candle and a grade A source.

New observations of the Crab Nebula have been reported at both high and low energies. CELESTE, with a threshold energy of 50 GeV, observed it for just three hours [13] whereas STACEE, with an interim threshold of 75 GeV, had a 7σ detection in 50 hours of observation [12]. Neither experiment could quote a flux value and neither experiment saw any evidence for a pulsed component from the Crab pulsar.

At higher energies the Crab was seen for the first time by a conventional air shower array (the Tibet High Density Array at 4.5 km) [11]. The energy threshold was 3 TeV and the flux deduced (see Table 1) was a factor of 2-3 higher than that seen in ACT experiments.

PSR 1706-44

Following the TeV detection of this source by the CANGAROO group [14] and its confirmation by the Durham group [15], there have been no new reports of observations. No periodic emission is seen and it is believed that the VHE emission comes from a weak plerion. Although weaker than the Crab this may be the standard candle for the southern hemisphere and merits a grade A ranking.

SN1006

In 1997 the CANGAROO Collaboration reported the observation of TeV γ -ray emission from the shell-type SNR, SN1006 [16]. Observations taken in 1996 and

1997 indicated a statistically significant excess from the northeast rim of the SNR shell. The flux at $> 1.7 \pm 0.5$ TeV was $(4.6 \pm 0.6(\text{sys}) \pm 1.4(\text{stat}) \times 10^{-12}$ photons $\text{cm}^{-2} \text{s}^{-1}$. The observations were motivated by the observation of non-thermal X-rays by the *ASCA* experiment [17]. It represented the first direct evidence of acceleration of particles to TeV energies in the shocks of SNRs.

At this workshop there was the disturbing report from the Durham group of the failure to detect this source in 40 hours of observation. Their upper limit at 300 GeV was 1.7×10^{-12} photons $\text{cm}^{-2} \text{s}^{-1}$ and at 1.5 TeV was 1.3×10^{-12} photons $\text{cm}^{-2} \text{s}^{-1}$, barely compatible with the CANGAROO observation. They point out that the presence of a bright star near the SNR complicates the measurement. Because of this report I assign this source a B- grade.

Vela

The CANGAROO group reported the detection of a 6σ signal from the vicinity of the Vela pulsar [18]. The integral γ -ray flux above 2.5 TeV is 2.5×10^{-12} photons $\text{cm}^{-2} \text{s}^{-1}$. There is no evidence for periodicity and the flux limit is about a factor of ten less than the steady flux. The signal is offset (by 0.14°) from the pulsar position which makes it more likely that the source is a synchrotron nebula. Since this offset position is coincident with the birthplace of the pulsar it is suggested that the progenitor electrons are relics of the initial supernova explosion and they have survived because the magnetic field was weak.

Again the source was not confirmed by observations by the Durham group (J.Osborne, this workshop). The upper limit to the γ -ray flux above 300 GeV is 5×10^{-11} photons $\text{cm}^{-2} \text{s}^{-1}$. Given the differences in energy and the uncertainties in flux estimates in the two experiments, the Durham group felt the two results were compatible. However it would have been reassuring to see the independent confirmation. I give this one a B grade.

RXJ1713.7-3946

The detection of TeV gamma-rays from this shell-type SNR was reported by the CANGAROO group for the first time this year [19]. The observations were motivated by the observation of a hard X-ray power-law spectrum by *ASCA* [20]. In this respect, it is very similar to SN1006 but is three times brighter in X-rays. It has a characteristic dimension of 70 arc-min, lies at a distance of 1.1 kpc and has an estimated age of 2,100 years. The γ -ray flux above 2 TeV is 3×10^{-12} photons $\text{cm}^{-2} \text{s}^{-1}$ with a 5σ significance. There is evidence that the source is extended in the same direction as the X-ray source. This is clearly a grade B source.

Cassiopeia A

It is natural that the strongest source in the radio sky should have been one of the first targets of TeV observations [21]. It is appropriate that it should have been eventually detected as a TeV source; however this only came after a very long exposure by the HEGRA group [22]. As with SN1006 and RXJ1713.7-3946, these observations were motivated by observations of a hard X-ray power-law spectrum

TABLE 2. Observations of Cassiopeia A

Group	E_{th} (TeV)	Exposure (hours)	Integral Flux (10^{-11} photons $\text{cm}^{-2} \text{s}^{-1}$)
Whipple	500	7.5	< 0.66
CAT	400	24.4	< 0.74
HEGRA	1000	127.9	≈ 0.3

[23]. The source is a classical shell-SNR of diameter 2.2 arc-min which is effectively point-like to a γ -ray telescope. It is believed to be 300 years old and there is no active pulsar at its center; however there may be a neutron star. The HEGRA observations were made in 1997 and 1998 and comprised some 130 hours on the source. The flux above 1 TeV has not yet been determined but must be $\approx 3 \times 10^{-12}$ photons $\text{cm}^{-2} \text{s}^{-1}$. The total detection was just less than 5σ and it is probably the weakest TeV source detected to date.

Upper limits to the TeV emission have been reported by the CAT [24] and Whipple [25] groups. These were at lower energies but, because the exposures were much shorter, the upper limits are compatible with the HEGRA detection. The three results are summarized in Table 2.

Because the detection is below the magic 5σ level and Cassiopeia A is the weakest source yet detected (and hence more susceptible to systematic effects), I give this a C grade for now.

Centaurus X-3

New observations were reported on the high mass X-ray binary, Cen X-3 [26]. The system contains a 4.8 s pulsar in orbit with a period of 2.1 days. Originally reported as a source of sporadic outbursts of pulsed emission [27,28], it was later found to be a source of steady (unpulsed) weak emission [29]. At this time it was also seen as an unpulsed GeV EGRET source [30]. The new observations, taken in 1998 and 1999 by the Durham group, do not add to the overall statistical significance of the detections which remain somewhat marginal; hence I give it a C grade.

B Extragalactic Sources

Markarian 421

Markarian 421 was one of the weakest AGNs detected by EGRET; it was also the closest BL Lac at $z = 0.031$. It was the first TeV source detected [31]. It is also the AGN in which the clearest correlations have been found over multiple wavelengths (see [2]) and in which the shortest time variations have been seen [32]. At discovery, its intensity was approximately 30% of the Crab; however it has flared to levels more than ten times greater than the Crab.

In 1998 there were extensive multiwavelength campaigns on this source between various ground-based γ -ray observatories and the *ASCA* and *BeppoSAX* X-ray satellites [33,34]. The most interesting event was the flare seen on April 21, 1998 by the Whipple Observatory [35] and the *BeppoSAX* telescopes. Although the flare was observed to rise and peak at the same time in both telescopes, the TeV signal decayed within a few hours whereas the X-ray signal persisted for half a day. It is difficult to model this behavior.

The energy spectrum of Markarian 421 has been reported by several groups. There is general agreement that it can be fit by a simple power law. While the absolute flux has little meaning since it varies with time, the differential power-law spectral index should be comparable in different experiments unless it is also variable with time. There is good agreement on the indices obtained thus far by CAT ($-2.96 \pm 0.13 \pm 0.05$) [36]; HEGRA ($-3.09 \pm 0.07 \pm 0.10$) [37]; 7TA (-2.81) [38]. However the Whipple group gets consistently harder spectra [39] particularly during flaring e.g (-2.54 ± 0.04) on May 7, 1996. Preliminary analysis of non-flaring data gives a similar result. Obviously further work is required here to ensure that the analysis is free of large systematic errors.

Despite its variability Markarian 421 is well-established and merits an A grade.

Markarian 501

Markarian 501, a BL Lac at $z=0.034$, was the first extragalactic γ -ray source detected first at TeV energies. Originally detected as a weak source (8% Crab) [40] it has been intensively monitored by ground-based telescopes since then. The TeV outburst from Markarian 501 in 1997 merited a Highlight session at the 25th ICRC [41]. Sadly while the conference was taking place the source was already in decline and it has been relatively quiescent ever since. Most of the interest in the source since that time has been in a detailed analysis of the high intensity signal, in particular in the derivation of an accurate energy spectrum.

The 1997 outburst data has been summarized in a number of publications [42–45]. Variations with doubling times as short as two hours have been reported [42] but in general the variations are not as short as those seen in Markarian 421. There were no significant new results from multiwavelength campaigns.

Spectral measurements were in agreement in that the energy spectrum could not be satisfactorily represented by a simple power law. The Whipple and HEGRA groups [46,39]) reported that they observed no change in spectral shape with source intensity; in contrast, the CAT group [47] using a simple Hardness ratio found that the spectrum hardened as the intensity increased. It is not clear whether this is a real change or the result of the systematics in a new analysis method (which has not yet been tested on any other source). In addition the CAT group reported that the weak intensity emission observed in 1998 could be best fit by a simple power law with differential spectral index -2.97 ± 0.20 .

Markarian 501 is the archetypical extreme BL Lac, characterized by its low luminosity, its high synchrotron peak (up to 100 keV), and its high Compton peak (up to TeV) [51,49]. As the strongest source (for a few months in 1997) thus far

observed, it clearly merits an A grade.

1ES2344+514

Although less well-studied, this X-ray-selected BL Lac at $z=0.044$ is superficially very similar to the above two sources. Recent X-ray observations by *Beppo-SAX* [50] emphasize this similarity: time variability on times scales of hours has been seen and the putative synchrotron spectrum peaks at energies greater than 10 keV. It was reported as a TeV source [51] primarily on the basis of a flare seen in one night at the 6σ level; the average flux over that night was $F_\gamma (>350 \text{ GeV}) = (6.6 \pm 1.9) \times 10^{-11} \text{ photons cm}^{-2} \text{ s}^{-1}$ which was 60% of the Crab. The averaged flux (including the flare) was at the 5.8σ level. The source was not detected in the 1996/7 observing season.

Based on the observed behavior of Markarian 421 and Markarian 501 it might have been expected that continued monitoring of 1ES2344+514 would have confirmed this detection and given more information about its properties at high energies. In practice, continued monitoring by the Whipple group and HEGRA [52] have not confirmed either the flaring or steady emission; hence this source which would have been ranked B in 1997 must now have a C grade.

PKS2155-304

The above three sources are in the northern hemisphere; it had been predicted that PKS2155-304 would be the best candidate for TeV emission in the southern hemisphere. An X-ray-selected BL Lac, it has been detected by EGRET and has been the object of numerous multiwavelength observing campaigns. The Durham group detected it in 1996 and 1997 [53]; the November 1997 observations were particularly interesting as they coincided with observations by EGRET and RXTE which indicated that the source was active at this time.

More recent observations by the Durham group (J.Osborne, this workshop) have not detected the source. Because of its relatively large redshift ($z=0.116$), the energy spectrum of this source is of particular interest; however none is yet available. This appears to be a highly probable source and thus merits a B grade.

1ES1958-650

The Utah Seven Telescope Array group have reported the detection of the BL Lac, 1ES1958+650 based on 57 hours of observation in 1998 [38]. As with the four AGNs listed above, this is an X-ray-selected BL Lac; its redshift is 0.048. The energy threshold for these observations was 600 GeV. The flux level was not reported but the total signal was at the 3.9σ level. This is not normally considered high enough to claim the detection of a new source; however, within this database there were two epochs which were selected a posteriori which gave signals above the canonical 5σ level. This source has not yet been confirmed by any other group; it was observed by the Whipple group but no flux was detected [55]. It is therefore

awarded a B– grade.

3C66A

This is potentially the most exciting TeV detection of an AGN as it is quite different from the other AGNs. The source is a radio- selected, EGRET-detected, BL Lac and the redshift is 0.44, i.e., much more distant than the other objects. The Crimean Astrophysical Observatory group using the GT-48 telescope detected this source at the 5σ level in 1996 [56]. The flux above 900 GeV was $(3 \pm 1) \times 10^{-11}$ photons $\text{cm}^{-2} \text{s}^{-1}$. There were previous and later upper limits to the TeV emission from the source, e.g. $F_\gamma (> 350 \text{ GeV}) < 1.9 \times 10^{-11}$ photons- $\text{cm}^{-2}\text{s}^{-1}$ from Whipple in 1993 [57]. Confirmation of this detection is urgently required; until then it must be considered a grade C source.

V PERIODICITY IN 1997 SIGNAL FROM MRK 501

Several groups have reported on the apparent periodicity in the TeV γ -ray signal from Markarian 501 (TA, HEGRA, Whipple). The best data base is that of the HEGRA group since they observed during part of the bright period of the moon with one of their telescopes and hence have a database that is less prone to aliases. The reported periodicities occurred at 12.7 day [45] and 23-24 day [58,59] and S.Fegan, this workshop, and were arrived at using the Lomb method which is recommended for observations made at irregular intervals. The epoch chosen by the HEGRA group for periodicity analysis is *a posteriori* but coincides with the bulk of the TeV observations and the peak in the γ -ray signal intensity. There is no evidence for periodicity outside this interval, either in 1997 or in other years. A visual inspection shows that the γ -ray signal has a few clearly defined flares with several time constants and the most obvious is at 23 days.

Since all the γ -ray experiments were observing at approximately the same time, they must see the same time variations; hence reports from the separate experiments do not constitute independent confirmations. The real question is whether the observed "periodicity" is really statistically significant given the large number of time variations. It is difficult to arrive at the real statistical significance of the observed effect.

Similar periodicity is seen in the X-ray signal by ASM/ RXTE and it has been suggested that this constitutes independent evidence for the periodicity. However, correlation between the X-ray and TeV γ -ray signals from Markarian 421 and 501 on a variety of time-scales now seems to be well-established so that the independent analysis of the RXTE database only confirms this correlation, not the statistical significance of the periodicity.

The conclusion is that while there is apparent periodicity in the TeV/X-ray signals from Markarian 501 for a five month epoch in 1997, it is almost impossible to arrive at a definitive conclusion about its statistical significance.

Those who survived the many pseudo-periodicities seen in the "a posteriori"

TABLE 3. The TeV Source Catalog c.1999

Source	Type	Discovery	EGRET	Grade
Galactic				
Crab Nebula	Plerion	1989	yes	A
PSR 1706-44	Plerion?	1995	no	A
Vela	Plerion?	1997	no	B
SN1006	Shell	1997	no	B–
RXJ1713.7-3946	Shell	1999	no	B
Cassiopeia A	Shell	1999	no	C
Centaurus X-3	Binary	1999	yes	C
Extragalactic				
Markarian 421	XBL $z=0.031$	1992	yes	A
Markarian 501	XBL $z=0.034$	1995	yes	A
1ES2344+514	XBL $z=0.044$	1997	no	C
PKS2155-304	XBL $z=0.116$	1999	yes	B
PKS1959+650	XBL $z=0.048$	1999	no	B–
3C66A	RBL $z=0.44$	1998	yes	C

analysis of the TeV observation of binaries in the previous decade will perhaps be forgiven a little skepticism in the discussion of this new and potentially important result. It is unlikely that it will become credible until the phenomenon is observed again, either in Markarian 501 or another BL Lac.

VI GAMMA RAY BURST GRB970417A

At this workshop there was the first report of the detection of a γ -ray burst at TeV energies by Milagro, the first stage of the Milagro experiment (J.McEnery, this workshop). In some 15 months of operation 54 possible GRBs were within the FOV of the detector and from one of these, GRB970417a, 18 events were detected during the duration of the BATSE burst (9 s) where the background was 3.46 events. Allowing for trials, the probability of the observation being a statistical fluctuation was calculated to be 1.5×10^{-3} . The energy threshold was about 1 TeV and the flux a few times 10^{-12} photons- $\text{cm}^{-2}\text{-s}^{-1}$. Given the importance of a detection of a TeV burst it would seem wise to await a confirmation from the full, more sensitive, Milagro array before too many conclusions are drawn. The BATSE fluence of GRB970417a was 1.5×10^{-7} erg cm^{-2} , a rather weak burst, and there was nothing otherwise unusual about it. There was no precise position and hence no information on X-ray or optical counterparts nor any indication as to distance.

TABLE 4. Status of HE/VHE Sources

Energy Range	10 MeV - 10 GeV	300 GeV - 30 TeV
Platform	Space	Ground
Discrete Sources		
Type	No. of Sources	No. of Sources
AGNs	75	6
Normal Galaxies	1	0
Pulsars	5?	0
SNR Shell	4?	3
SNR Plerion	1	3
Binaries	1	1
Total identified	87	13
Unidentified	165	0
Total	250	13
Other Sources		
Galactic Plane	Yes	No
Extragalactic Diffuse	Yes	No
All Sky Survey	Yes	No
Gamma Ray Bursts	5	1?

VII HE/VHE STATUS AND OUTLOOK

Based on the above discussion the 1999 TeV Source catalog is derived (Table 3); it is disappointing that it is not much larger than the 1997 Catalog.

As we conclude this century it is worthwhile to summarize the progress in HE and VHE astronomy and compare the achievements in each band. The recent publication of the 3rd EGRET Catalog summarizes the field at energies from 30 MeV to 10 GeV.

In Table 4 the number of sources reported in various categories is compared. The 100 MeV sources are from the Third EGRET Catalog [60] and from [61]. Don Kniffen has pointed out (this workshop) that only a handful of the EGRET sources could be classified with an A grade. The TeV sources are from Table 3; note in this context C must be considered a passing grade.

Although EGRET has still some sensitivity the mission is essentially over and not much change can be expected in the observational picture until the launch of GLAST in 2005 (hopefully). The intermediate missions, AMS and AGILE, which are described elsewhere in these proceedings, will not significantly improve on the EGRET flux sensitivity and can be considered place- holders for GLAST. The latter will offer an improvement of a factor of 10-20 in most parameters compared to EGRET.

In contrast to the drought expected in MeV-GeV γ -ray observations in the immediate future, ground-based γ -ray astronomy has never been more active. There are already nine atmospheric Cherenkov imaging telescopes in operation and two low threshold air shower arrays; one can expect to see steady improvements in

TABLE 5. Future Roadmap for HE/VHE Gamma Ray Astronomy

Energy	MeV 10-100 Space	GeV 0.1-1 Space	GeV 1-10 Space	GeV 10-100 Space/ Ground	TeV 0.1-1 Ground	TeV 1-10+ Ground
Year						
1999	*Comptel*	(EGRET)		*****	**9ACITs*	***+2ASA
2000	****			CEL/STAC	*****	*****
2001	****			*****	*****	*****
2002	Integral			*****	*****	*****
2003	**	AMS/AGILE	*****	*MAGIC*	*****	*****
2003	**	*****	*****	*****	HESS/CAN	*****
2004	**	*****	*****	*****	VERITAS*	*****
2005	*GLAST**	**GLAST**	*GLAST*	*GLAST*	*****	*****
2006	*****	*****	*****	*****	*****	*****
2007	*****	*****	*****	*****	*****	*****
2008	*****	*****	*****	*****	*****	*****

sensitivity in these telescopes over the next decade. In addition, there are several other Cherenkov experiments coming on-line e.g., STACEE, CELESTE, Solar-Two, Pachmari, etc. Four major Cherenkov imaging telescopes/arrays are scheduled for completion by 2003, well in advance of GLAST and with significant overlap in the 30-300 GeV range. One can expect to see a steady increase in the GeV-TeV source catalog from ground-based observations so that even if the GLAST launch were to be delayed there would be a healthy increase in activity in studies of γ -ray astrophysics at these high energies.

VIII WHERE HAVE ALL THE HADRONS GONE?

It is a matter of some disappointment for the many cosmic-ray physicists who entered the field of high energy γ -ray astronomy that none of the sources thus far detected, either at HE or VHE energies, can be positively identified with hadron progenitors. In the early days it was widely believed that γ -ray astronomy would finally solve the mystery of the origin of the cosmic radiation. However with the exception of the galactic plane (and the Large Magellanic Cloud) where we observe not the source of cosmic radiation but its interaction during propagation, every one of the sources detected so far can be attributed to a source in which electrons are the progenitor particles. In no source is the much heralded "bump" in the energy spectrum near 70 MeV seen. In some cases there are proponents of plausible models in which hadrons are the progenitors but there are equally vociferous proponents who would advocate electron models and in many cases these seem the more plau-

sible. Thus in the 40 plus years since the publication of Morrison's seminal paper [62] while we have learnt some interesting astrophysics we have come no closer to a definitive model of cosmic-ray origins.

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